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Quantum teleportation of an image

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Quantum teleportation lies at the heart of a variety of quantum technologies, most of which, however, focused on 2-dimensional qubit states only. A fundamental open challenge remains as to whether we can teleport multilevel qudit states with bipartite entanglement. Here, we demonstrate such a high-dimensional teleportation using photonic orbital angular momentum (OAM). We exploit “perfect vortices” for preparing high-dimensional yet maximal OAM entanglement and for performing faithful high-dimensional Bell state measurements (HDBSM) based on sum-frequency generation. We experimentally achieve the average teleportation fidelity 0.8788 ± 0.048 for a complete set of 3-dimensional mutually unbiased bases. More importantly, we succeed in realizing the first quantum teleportation of optical images, with the effective channel capacity $\kappa > 100$. Our scheme holds promise for future high-volume quantum image transmission.

Since the seminal proposal by Bennett *et al.*¹, quantum teleportation has aroused numerous attentions²⁻²⁴ as its attractive potentials in some advanced and practical quantum information protocols, e.g., realizing quantum repeaters in long-distance quantum communication²⁵, constructing distributed quantum networks²⁶, and conducting measurement-based quantum computation^{27,28}. Hitherto, quantum teleportation has been reported in different quantum systems, such as flying photons²⁻⁴, nuclear magnetic resonance (NMR)⁷, atom ensembles¹⁰⁻¹², solid-state systems¹⁹, and even thermal light source²⁴. Recently, teleportation distance has been broadened to a global scale based on satellite-based photonic entanglement²⁰. It is noted that most of these previous schemes focused on the two-dimensional qubit systems only.

Recent years have also witnessed a growing interest in the high-dimensional or multi-level quantum systems²⁹, qudits, as it can offer higher information capacity, greater resilience to noises and eavesdropping^{30,31}, and more efficient quantum logic gates³². However, these benefits are only conceivable when we are able to efficiently prepare, manipulate, and measure the genuine high-dimensional quantum states. In particular, bipartite high-dimensional Bell state measurement (HDBSM) is essential for high-dimensional dense coding and quantum teleportation. Several attempts have been made, by means of ancillary photonic bits, to perform the 3-dimensional BSM and to demonstrate the qutrit teleportation, which is encoded by the photon path^{22,23}. However, since the number of the required ancillary bits increases significantly with the teleportation dimensionality in the linear optical detection schemes³³, the experimental teleportation of an arbitrary high-dimensional quantum states remains challenging.

Here we demonstrate such a high-dimensional teleportation, by exploiting perfect vortices to prepare high-dimensional yet maximally entangled OAM states and by employing sum-frequency generation to perform faithful high-dimensional Bell state measurements (HDBSM). Furthermore, we report the first quantum teleportation of optical images, and characterize its high-dimensional feature across the multi-pixel field of view in our quantum image teleporter system.

Results

Twisted photons carrying OAM possesses an inherent capacity for constructing a high-dimensional Hilbert space, thus making it a promising candidate for high-dimensional quantum information processing³⁴. It was Allen and coworkers³⁵ that recognized that the Laguerre-Gaussian (LG) modes of helical phase $\exp(i\ell\phi)$

$\ell\hbar$. We note that the OAM entanglement of photon pairs produced by spontaneous parametric down-conversion inevitably suffers from the limited spiral bandwidth³⁶, i.e., lower-order LG modes appears more frequently than higher-order ones. However, the maximal entanglement is prerequisite for a standard quantum teleportation. To overcome this obstacle, we adopt the modified LG modes, the so-called “perfect vortices³⁷”, to represent OAM eigenstate, $|\ell\rangle$, see the **Methods** for details. As a result, entanglement concentration is implemented naturally, leading to the high-dimensional yet maximal OAM entanglement. In our experimental demonstration, we first realize the quantum teleportation of 3-dimensional OAM states, qutrits. Assume Alice wishes to teleport to Bob the OAM qutrit state of photon a , $|\varphi\rangle_a = \alpha_1|-1\rangle_a + \alpha_2|0\rangle_a + \alpha_3|1\rangle_a$, where the complex coefficients $\alpha_1, \alpha_2, \alpha_3$ fulfill

$|\alpha_1|^2 + |\alpha_2|^2 + |\alpha_3|^2 = 1$. For teleporting such an arbitrary 3-dimensional states, Alice and Bob need share the aforementioned bipartite high-dimensional and maximally entangled state (photons b and c),

$$|\Psi\rangle_{bc} = \frac{1}{\sqrt{3}}(|-1,1\rangle_{bc} + |0,0\rangle_{bc} + |1,-1\rangle_{bc}). \quad (1)$$

Then, the whole state of these three photons can be written as,

$$\begin{aligned} |\Psi\rangle_{abc} = \frac{1}{3} & \{ |\psi_{00}\rangle_{ab} (\alpha_1|-1\rangle_c + \alpha_2|0\rangle_c + \alpha_3|1\rangle_c) + \\ & |\psi_{01}\rangle_{ab} (\alpha_1\omega|-1\rangle_c + \alpha_2|0\rangle_c + \alpha_3\omega^2|1\rangle_c) + \\ & |\psi_{02}\rangle_{ab} (\alpha_1\omega^2|-1\rangle_c + \alpha_2|0\rangle_c + \alpha_3\omega|1\rangle_c) + \\ & |\psi_{10}\rangle_{ab} (\alpha_1|1\rangle_c + \alpha_2|-1\rangle_c + \alpha_3|0\rangle_c) + \\ & |\psi_{11}\rangle_{ab} (\alpha_1\omega|1\rangle_c + \alpha_2|-1\rangle_c + \alpha_3\omega^2|0\rangle_c) + \\ & |\psi_{12}\rangle_{ab} (\alpha_1\omega^2|1\rangle_c + \alpha_2|-1\rangle_c + \alpha_3\omega|0\rangle_c) + \\ & |\psi_{20}\rangle_{ab} (\alpha_1|0\rangle_c + \alpha_2|1\rangle_c + \alpha_3|-1\rangle_c) + \\ & |\psi_{21}\rangle_{ab} (\alpha_1\omega|0\rangle_c + \alpha_2|1\rangle_c + \alpha_3\omega^2|-1\rangle_c) + \\ & |\psi_{22}\rangle_{ab} (\alpha_1\omega^2|0\rangle_c + \alpha_2|1\rangle_c + \alpha_3\omega|-1\rangle_c) \}, \end{aligned} \quad (2)$$

where $|\psi_{mn}\rangle = \frac{1}{\sqrt{3}} \sum_{\ell=-1}^1 \exp(i2n\ell\pi/3) |\ell\rangle |-\ell \oplus m\rangle$ forms the complete Bell basis in 3-dimensional OAM subspace, with $m, n \in \{0,1,2\}$ and $\omega = \exp(i2\pi/3)$. Alice routinely needs to distinguish these 9 Bell states by performing HDBSM on photons a and b , and then communicates her measurement results to Bob via a classical channel. Accordingly, Bob conducts the desired unitary operations on photon c to recover the original state, and thus accomplishing the teleportation task reliably.

As was well known, HDBSM remains technically challenging in linear optical schemes. Instead, we adopt the nonlinear optical process of SFG to measure the complete Bell basis. By a careful analysis on the OAM conversion behaviors in SFG

process, we find that the desired 9 Bell states can all be identified equivalently. First, Alice can mix photons a and b directly in the nonlinear crystal. Owing to OAM conservation in the process of SFG³⁸, we can map the following 7 two-photon OAM Bell states onto 7 single-photon OAM superposition states, respectively, that is,

$$\begin{aligned}
|\psi_{00}\rangle_{ab} &\rightarrow |0\rangle, \\
|\psi_{10}\rangle_{ab} &\rightarrow |-2\rangle + 2|1\rangle, \\
|\psi_{11}\rangle_{ab} &\rightarrow \omega^2 |-2\rangle + (\omega + 1)|1\rangle, \\
|\psi_{12}\rangle_{ab} &\rightarrow \omega |-2\rangle + (\omega^2 + 1)|1\rangle, \\
|\psi_{20}\rangle_{ab} &\rightarrow |2\rangle + 2|-1\rangle, \\
|\psi_{21}\rangle_{ab} &\rightarrow (\omega^2 + 1)|-1\rangle + \omega|2\rangle, \\
|\psi_{22}\rangle_{ab} &\rightarrow (\omega + 1)|-1\rangle + \omega^2|2\rangle.
\end{aligned} \tag{3}$$

Of particular importance is the generated OAM state of $|\psi_{00}\rangle_{ab}$ is orthogonal to the rest of Bell states. While for $|\psi_{01}\rangle_{ab}$ and $|\psi_{02}\rangle_{ab}$, the SFG for photons a and b is forbidden, as a result of the destructive interference in SFG light fields. Still, we can identify $|\psi_{01}\rangle_{ab}$ and $|\psi_{02}\rangle_{ab}$ by performing a prior OAM-dependent phase shifts on photon a . This can be done simply by inserting into photon a 's path one Dove prism (DP)³⁹, whose orientation is adjusted at an angle of $-\pi/3$ and $\pi/3$, respectively, to convert $|\psi_{01}\rangle_{ab}$ and $|\psi_{02}\rangle_{ab}$ to $|\psi_{00}\rangle_{ab}$. By projecting the SFG photons onto the $|-2\rangle + |1\rangle$ and $|2\rangle + |-1\rangle$, we can also identify $|\psi_{10}\rangle_{ab}$ and $|\psi_{20}\rangle_{ab}$, respectively. Similarly, by performing a prior OAM-dependent phase shifts on photon a , we can also convert $|\psi_{11}\rangle_{ab}$ and $|\psi_{12}\rangle_{ab}$ to $|\psi_{10}\rangle_{ab}$, $|\psi_{21}\rangle_{ab}$ and $|\psi_{22}\rangle_{ab}$ to $|\psi_{20}\rangle_{ab}$, respectively. Note that, in addition to preparing the OAM maximal entanglement, the use of perfect vortices is also essential for the faithful SFG-based HDBSM, as it guarantees the identical conversion efficiency for different input OAM modes. In other words, the

deterministic high-dimensional teleportation could be realized with our scheme of perfect-vortex-encoded and SFG-based faithful HDBSM in the OAM subspace.

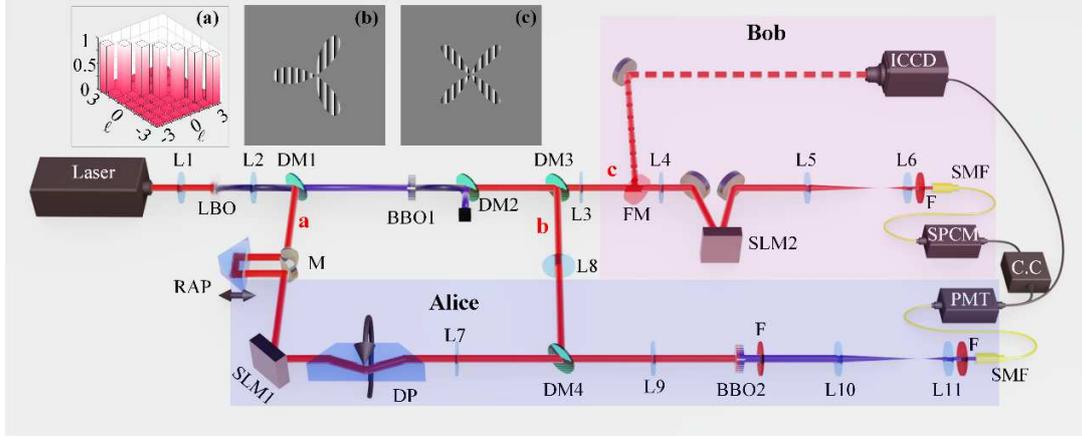


Fig. 1 | Experimental setup for quantum teleportation of high-dimensional OAM states and optical images. Inset (a) shows the measured two-photon 7-dimensional OAM spectrum, (b) and (c) illustrate the holographic gratings used for encoding the three-leaf Clover and four-leaf Clover images to be teleported. By switching the flipper mirror (FM), full tomography for the teleported OAM superposition states and the capture of the teleported images can be conducted by using the coincidence circuit (C.C) and the ICCD camera, respectively. See the **Methods** for details.

Figure 1 illustrate our experimental setup for high-dimensional OAM teleportation and the image teleportation. The light beam derived from a mode-locked Ti-sapphire laser has a central wavelength of 710 nm and a duration of 140 fs. We first direct the laser beam to the Lithium triborate crystal (LBO), via second-harmonic generation, to generate the ultraviolet pulses centered at 355 nm. The residual 710nm light is guided onto a spatial light modulator (SLM1) that displays suitable holograms for preparing photon a in the desired high-dimensional OAM superpositions to be teleported. While the generated 355 nm ultraviolet pulses are directed to pump the β -barium borate crystal (BBO1) to create the non-degenerate OAM-entangled photon pairs via spontaneous

parametric down-conversion (SPDC), i.e., photon b and c , centered at 780 nm and 650 nm, respectively. Alice possesses photon a and b while Bob holds photon c . In order to teleport the high-dimensional OAM states encoded by photon a onto photon c , Alice performs the HDBSM on her photon a and b , by sending them together to another BBO2 to do SFG. The 372nm SFG photon is then coupled to a single-mode fiber (SMF) and detected by a Photo Multiplier Tube (PMT). As mentioned above, Alice is able to identify all 9 Bell states by prior suitable OAM manipulations and state filtering. Thus the single-photon event from PMT at Alice's side indicates the faithful HDBSM and heralds a teleported photon c at Bob's side.

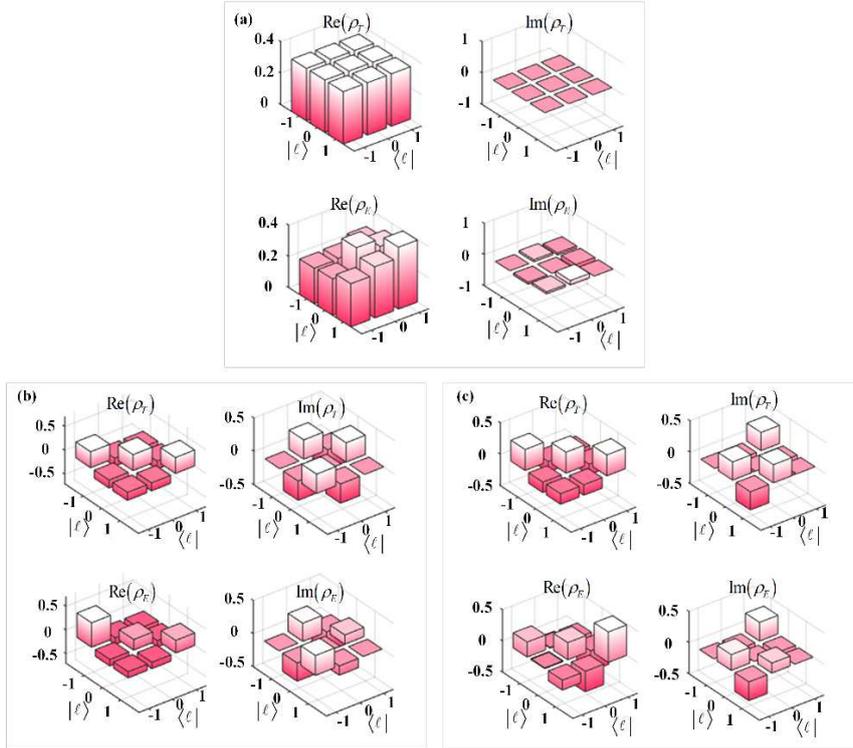


Fig. 2 | Density matrices for 3-dimensional OAM teleportation, $|\varphi_4\rangle_a = (|-1\rangle_a + |0\rangle_a + |1\rangle_a)/\sqrt{3}$, conditional on three specific HDBSMs: (a) $|\psi_{00}\rangle_{ab}$, (b) $|\psi_{01}\rangle_{ab}$ and (c) $|\psi_{02}\rangle_{ab}$. In each case, the upper rows are the original real and imaginary parts while the bottom are the experimental results.

In our first set of experiment, we prepare 12 OAM states to be teleported at Alice's

$$\begin{aligned}
|\varphi_1\rangle_a &= |-1\rangle_a, & |\varphi_2\rangle_a &= |0\rangle_a, & |\varphi_3\rangle_a &= |1\rangle_a, & |\varphi_4\rangle_a &= (|-1\rangle_a + |0\rangle_a + |1\rangle_a)/\sqrt{3}, \\
|\varphi_5\rangle_a &= (|-1\rangle_a + \omega|0\rangle_a + \omega^2|1\rangle_a)/\sqrt{3}, & |\varphi_6\rangle_a &= (|-1\rangle_a + \omega^2|0\rangle_a + \omega|1\rangle_a)/\sqrt{3}, \\
|\varphi_7\rangle_a &= (\omega|-1\rangle_a + |0\rangle_a + |1\rangle_a)/\sqrt{3}, & |\varphi_8\rangle_a &= (|-1\rangle_a + \omega|0\rangle_a + |1\rangle_a)/\sqrt{3}, \\
|\varphi_9\rangle_a &= (|-1\rangle_a + |0\rangle_a + \omega|1\rangle_a)/\sqrt{3}, & |\varphi_{10}\rangle_a &= (\omega^2|-1\rangle_a + |0\rangle_a + |1\rangle_a)/\sqrt{3}, \\
|\varphi_{11}\rangle_a &= (|-1\rangle_a + \omega^2|0\rangle_a + |1\rangle_a)/\sqrt{3}, & \text{and } |\varphi_{12}\rangle_a &= (|-1\rangle_a + |0\rangle_a + \omega^2|1\rangle_a)/\sqrt{3}.
\end{aligned}$$

They constitute the full four sets of 3-dimensional mutually unbiased bases (MUB), which are commonly used to testify the universality of teleportation for all possible superpositions states⁴⁰. The verification of teleportation results is based on the two-fold coincidence detections between the SFG photon (detected by PMT) and photon c (detected by SPCM). After teleportation, we employ the generalized Gell-Mann matrix basis⁴¹ to reconstruct the density matrices of photon c at Bob's side. Then the effectiveness of our high-dimensional teleportation can be confirmed quantitatively by calculating the teleportation fidelity, $F = \text{Tr}(\rho_E \rho_T) + \sqrt{1 - \text{Tr}(\rho_E^2)} \sqrt{1 - \text{Tr}(\rho_T^2)}$, where ρ_E and ρ_T represent the density matrices of the experimentally measured states and the original ones, respectively. We present in Fig. 2 the teleportation results for a qutrit OAM state, $|\varphi_4\rangle_a = (|-1\rangle_a + |0\rangle_a + |1\rangle_a)/\sqrt{3}$, without loss of generality, conditional on three different specific HDBSM. Specifically, Figure 2(a), 2(b), and 2(c) show the resultant density matrices conditional on HDBSM results of $|\psi_{00}\rangle_{ab}$, $|\psi_{01}\rangle_{ab}$, and $|\psi_{02}\rangle_{ab}$, respectively, in each of which the upper rows are the original real and imaginary parts while the bottom are the experimentally reconstructed ones. The fairly good agreement between them can be seen clearly. For quantitative analysis, we also show in Fig. 3 the teleportation fidelities for all 12 MUB states conditional on these

0.8788 ± 0.048 , with 7.89 standard

deviations above the classical limit 0.5. Note that all these experimental results are obtained without any background subtraction. Besides, the imperfect spatio-temporal overlap of photons a and b at BBO2 is the main limited factor for a better teleportation performance.

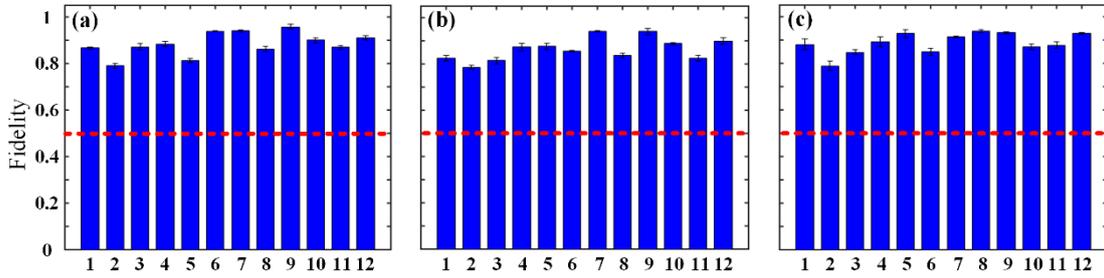


Fig. 3 | Experimental teleportation fidelities for all 12 OAM MUB states condition on three specific HDBSM results: (a) $|\psi_{00}\rangle_{ab}$, (b) $|\psi_{01}\rangle_{ab}$, and (c) $|\psi_{02}\rangle_{ab}$. The labels of 1-12 in the horizontal axis represent the OAM qutrit states, $|\varphi_1\rangle_a - |\varphi_{12}\rangle_a$. The red dashed lines indicate the nonclassical quantum teleportation bound $1/2$.

Our quantum teleportation scheme for the above OAM qutrit states can be straightforwardly extended to embrace any higher-dimensional states. As is well known, any 2D optical image can be equivalently represented by a high-dimensional state vector encoded in the photonic spatial degrees of freedom, e.g., according to the digital spiral imaging concept^{43,44}. In this regard, quantum image teleportation can be reckoned as the ultimate goal of high-dimensional teleportation. Besides, the vision or image is by far the most universal carrier for transferring information in the real world. Therefore, quantum image teleportation is also highly desirable for future high-capacity complex

quantum network. For such a quantum image teleporter, Alice and Bob share the photon pairs that are entangled in the full transverse spatial modes, which can be written in terms of LG modes as³⁶, $|\Psi\rangle_{bc} = \sum_{\ell,p} C_{p,p}^{\ell,-\ell} |\ell,p\rangle_b |-\ell,p\rangle_c$, where $C_{p,p}^{\ell,-\ell}$ denotes the probability amplitude of finding photon b in the mode of $|\ell,p\rangle$ and the photon c in the mode of $|-\ell,p\rangle$. The full transverse spatial mode entanglement has been explored for full-field quantum imaging and quantum pattern recognition⁴⁵. However, it has not yet been explored for quantum image teleportation. For this, at Alice's side, the real-amplitude images, e.g., three-leaf and four-leaf clover, are taken as examples for such a purpose. They are prepared and encoded by photon a with the holograms displayed by SLM1, see the insets of Fig. 1(b) and 1(c). As mentioned above, the transmission function of any optical image, $O(r,\phi)$, can be equivalently represented by a high-dimensional vector state as, $|\varphi\rangle_a = \sum_{\ell_a,p_a} A_{\ell_a,p_a} |\ell,p\rangle_a$, where $A_{\ell_a,p_a} = \iint [LG_{p_a}^{\ell_a}(r,\phi)]^* O(r,\phi) r dr d\phi$. Similarly, Alice mixes photons a (bearing the image information) and photon b in the BBO2 crystal to conduct SFG, and then filters out the fundamental mode of SFG photons using a SMF that is connected to a PMT. Owing to OAM conservation in the process of SFG³⁸, the generated SFG photons can be collected by the SMF only when $\ell_a = -\ell_b$ and $p_a = p_b$. Consequently, the photon c at Bob's side is collapsed onto $|\varphi\rangle_c = \sum_{\ell_c,p_c} A_{\ell_c,p_c} \eta_{p_c,p_c}^{\ell_c,-\ell_c} C_{p_c,p_c}^{\ell_c,-\ell_c} |\ell,p\rangle_c$, where $\eta_{p_c,p_c}^{\ell_c,-\ell_c}$ denotes the frequency up-conversion efficiency for $LG_{p_c}^{\ell_c}$ and $LG_{p_c}^{-\ell_c}$. For sufficiently large and strong pump beams, both $\eta_{p_c,p_c}^{\ell_c,-\ell_c}$ and $C_{p_c,p_c}^{\ell_c,-\ell_c}$ can be approximately a constant, which means a successful teleportation, that is, photon c just takes a perfect replica of the original state of photon a . Then, the single-photon events from PMT

indicates the HDBSM result $|\psi_{00}\rangle_{ab}$ at Alice's side, which serves the trigger signal for the ICCD camera at Bob's side to capture the image that is teleported onto photon c .

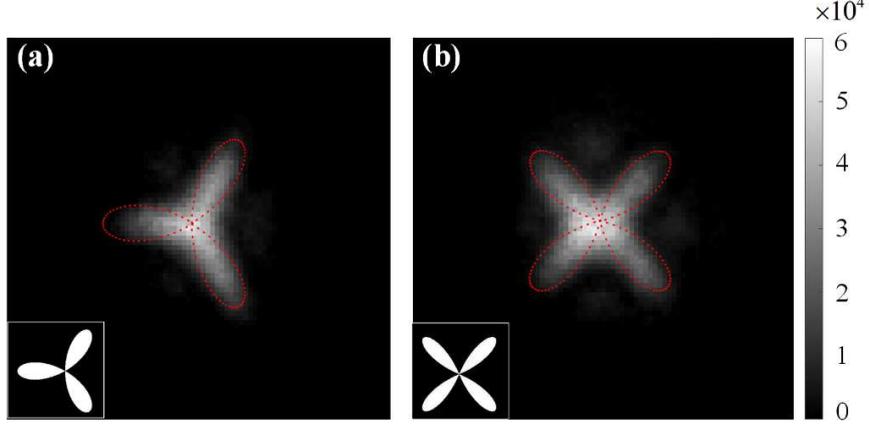


Fig. 4 | Experimental results for quantum image teleportation: (a) Three-leaf Clover and (b) four-leaf Clover. Insets show the original images. The gray-scale bar is in units of photons/pixel.

We present our experimental observations of the teleported three-leaf and four-leaf Clover images in Fig. 4(a) and 4(b), respectively. As shown by the dotted lines, we define the regions of interest (ROI) for both three-leaf and four-leaf Clover images, which occupy about 432 and 441 pixels, respectively. We can define the image fidelity as $F = \left| \sum_{k,j} I_E(k,j) I_O(k,j) \right|^2$, where $I_E(k,j)$ and $I_O(k,j)$ is the normalized amplitude at the pixel position (k,j) for the experimentally teleported image and the original one, respectively. We have $F = 0.5536$ and 0.4861 for three-leaf and four-leaf Clover images, respectively. We can attribute the low fidelity of quantum image teleportation mainly to both the non-maximal spatial entanglement for photon pairs generated by SPDC and the nonuniform SFG efficiency for each pixel in the HDBSM stage.

In our scheme, the teleported images are recorded and visualized directly with a

$|\varphi\rangle_{\text{image}} = \sum_{k,j} f(k,j)|k,j\rangle$, where the computational basis $|k,j\rangle$ encodes the pixel position (k,j) , and $f(k,j)$ represents the normalized pixel grayscale value, with $\sum_{k,j} |f(k,j)|^2 = 1$. A successful teleportation of an image means that individual pixel information should be teleported successfully. For two-photon maximal entanglement and a perfect HDBSM, the successful teleportation can be manifested by the teleported image that is identical to the original one. In other words, the pixelated images can offer an intuitive way to characterize the effective dimensionality of the nonlocal channels that sustain the quantum image teleportation, in which the Schmidt number⁴⁶ can be written as, $\kappa = 1/\sum_{k,j} |f(k,j)|^4$. Accordingly, from the experimentally recorded images by the ICCD camera, we can directly calculate the Schmidt numbers as $\kappa = 134.68$ and 106.33 , thus showcasing the high-dimensional feature of our quantum image teleporter systems.

Conclusion

In summary, we have demonstrated quantum teleportation of high-dimensional spatial modes and even a quantum image teleporter. The key to our scheme is the exploitation of perfect vortices both for making two-photon high-dimensional yet maximal OAM entanglement and for performing a high-effective yet faithful HDBSM via SFG. We have experimentally achieved the average teleportation fidelity of 0.8788 ± 0.048 for

a complete set of 3-dimensional MUB, significantly beyond the classical limit. More importantly, we succeed in realizing the first quantum image teleportation by exploring the full transverse spatial entanglement. We use the ICCD camera to capture the teleported images, and from the multi-pixel field of view, we estimate the effective channel capacity $\kappa > 100$, thus showcasing the inherent high-dimensional feature of our quantum image teleportation system. Our scheme is fundamentally different from previous quantum imaging techniques⁴⁷, such as ghost imaging⁴⁸ or quantum imaging with undetected photons⁴⁹. Our method holds promise for future high-volume and secure quantum image transmission.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at <https://doi.org/10.1038/...>

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Methods

Perfect vortices. Photon pairs generated by SPDC have proven to be a reliable entanglement source. However, under the thin-crystal approximation and phase-matching condition with a Gaussian pump beam, the down-converted two-photon OAM entanglement inevitably suffers from the limited spiral bandwidth³⁶, i.e., lower-order LG modes appears more frequently than higher-order ones. If the standard LG

modes are used to represent the OAM eigenstates $|\ell\rangle$, namely, $\langle r, \phi | \ell \rangle = \text{LG}_{p=0}^\ell(r, \phi)$, the two-photon OAM entangled state can be written as, $|\Psi\rangle_{bc} = \sum_\ell C_\ell |\ell\rangle_b |-\ell\rangle_c$, where $C_\ell = \int \text{LG}_0^0(r, \phi) [\text{LG}_0^\ell(r, \phi)]^* [\text{LG}_0^{-\ell}(r, \phi)]^*$ represents the probability amplitude of finding photon b in the mode of $|\ell\rangle$ and the photon c in the mode of $|-\ell\rangle$. As mentioned above, $|\Psi\rangle_{bc}$ is merely a non-maximally entangled OAM state. However, the maximal entanglement is prerequisite for a standard quantum teleportation. To overcome this obstacle, we adopt the so-called “perfect vortices” (37) to represent OAM eigenstate, instead of the standard LG modes. In our scheme, we prepare the perfect vortex states by modifying the LG modes as⁵⁰,

$$\text{MLG}_0^\ell(r, \phi) = |\text{LG}_0^l(r, \phi)| \exp(il\phi), \quad (4)$$

where l is a constant, e.g., $l=5$. In such a basis of perfect vortices, we know that $C_\ell = \int \text{LG}_0^0(r, \phi) [\text{MLG}_0^\ell(r, \phi)]^* [\text{MLG}_0^{-\ell}(r, \phi)]^*$ will become a constant, as they share the same intensity distribution and have the identical overlap probability. Thus, we can obtain the desired maximally entangled OAM state as,

$$|\Psi\rangle_{bc} = \frac{1}{\sqrt{d}} \sum_\ell |\ell\rangle_b |-\ell\rangle_c, \text{ with } d \text{ being the dimensionality of the OAM subspace.}$$

Besides, the perfect vortex is also crucial for performing the faithful HDBSM via SFG. Based on the couple-wave equations describing the SFG, we can estimate the frequency conversion efficiency for our perfect vortices of modified LG mode as⁵¹,

$$\eta_{\ell_a, \ell_b} \propto \int \text{MLG}_0^{\ell_a}(r, \phi) \text{MLG}_0^{\ell_b}(r, \phi) [\text{MLG}_0^{\ell_a + \ell_b}(r, \phi)]^* r dr d\phi. \quad (5)$$

Similarly, we can expect that η_{ℓ_a, ℓ_b} will become a constant even for different OAM modes, and thus realizing a faithful HDBSM.

$(f_1 = 150\text{mm})$ and guided to pump a 1.5-mm-long LBO crystal to generate the ultraviolet pulse of a central wavelength of 355 nm and an average power of 200 mW via second-harmonic generation (SHG). The residual 710nm light beam is collimated by L2 ($f_2 = 100\text{mm}$) and guided onto a spatial light modulator (SLM1), which is used to display suitable holographic gratings for preparing photon a in an arbitrary high-dimensional OAM superposition state to be teleported. After reflection from SLM1, the light beam has a power of roughly 140 mW. While the generated 355 nm SHG ultraviolet pulses are directed to pump a 3-mm-long β -barium borate crystal (BBO1) to create the frequency non-degeneracy OAM entangled photon pairs via SPDC, i.e., photon b and c , whose wavelengths are centered at 780 nm and 650 nm, respectively. A long-pass dichroic mirror (DM2) is inserted to separate the down-converted photons from the pump. For performing HDBSM, the 780 nm photon b reflected from DM3 and photon a are combined through DM4, and then sent to 1.5-mm-long BBO2 for implementing SFG. Note that, photon a and b are both imaged onto the BBO2 via $4f$ imaging systems, L7-L9 and L8-L9 ($f_7 = f_8 = 500\text{mm}$, $f_9 = 100\text{mm}$), to ensure a good spatial overlap of the image planes of BBO2, BBO1 and SLM1. In addition, the temporal overlap between photon a and b in BBO2 is realized by accurately adjusting the position of right-angle prism (RAP). Subsequently, we use another $4f$ system ($f_{10} = 500\text{mm}$ and $f_{11} = 300$) together with a 4 mm collimated lens to couple the

generated 372nm SFG photon into a single-mode fiber (SMF), which is connected to a Photo Multiplier Tube (PMT). The single-photon event from PMT indicates the successful BSM signal and herald a teleported photon c at Bob's side. For performing the state tomography, photon c is imaged onto SLM2 with a $4f$ imaging system ($f_3 = 200\text{mm}$ and $f_4 = 400\text{mm}$) and then reimaged onto the input facet of SMF with another $4f$ imaging system ($f_5 = 500\text{mm}$ and $f_6 = 10\text{mm}$). By switching the flipper mirror (FM), we can capture the teleported images by using the ICCD camera, which is triggered by the single-photon events from the PMT. Note that an image preserving optical delay of about 25m is requested to compensate the electronic delay associated with the PMT and the trigger mechanism in the ICCD camera⁴⁵.

Data availability

The datasets generated and analysed during this study are available from the corresponding author upon reasonable request.

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Author contributions

L.C. conceived the idea. L.C. and X.Q. designed the experiment. X.Q. conducted the experiment with the help from H.G. X.Q. and L.C. analyzed the data and co-wrote the manuscript. L.C. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

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